Latest Results From The DODO Survey: Imaging Planets Around White Dwarfs

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Abstract. The aim of the Degenerate Objects around Degenerate Objects (DODO) survey is to search for very low mass brown dwarfs and extrasolar planets in wide orbits around white dwarfs via direct imaging. The direct detection of such companions would allow the spectroscopic investigation of objects with temperatures lower ($<$ 500 K) than the coolest brown dwarfs currently observed. The discovery of planets around white dwarfs would prove that such objects can survive the final stages of stellar evolution and place constraints on the frequency of planetary systems around their progenitors (with masses between $1.5-8M_{\odot}$, i.e., early B to mid-F). An increasing number of planetary mass companions have been directly imaged in wide orbits around young main sequence stars. For example, the planets around HR 8799 and 1RXS J160929.1 $-$ 210524 are in wide orbits of $24-68$ AU and 330 AU, respectively. The DODO survey has the ability to directly image planets in post-main sequence analogues of these systems. These proceedings present the latest results of our multi-epoch *J* band common proper motion survey of nearby white dwarfs.

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INTRODUCTION

Directly imaging the extrasolar planets found in orbit around solar type stars is difficult as these faint companions are too close to their bright parent stars. However, an increasing number of planetary mass companions have been directly imaged in wide orbits around young main sequence stars. For example, three directly imaged companions, with likely masses between $5-13M_{\rm Jup}$ and projected physical separations of $\sim$ 24, 38 and 68 AU, were found around the A-type star HR8799 [23]. Another, more extreme example is the $\sim 8M_{\rm Jup}$ companion imaged at a surprisingly large separation of $\sim$ 330 AU around a member of the Upper Scorpius association, 1RXS J160929.1 $-$ 210524 [21]. All the imaged planetary mass companions found to date have been confirmed to be common proper motion companions to their parent stars. However, coronagraphy and adaptive optics were needed to detect these faint companions. Another, perhaps simpler, solution to the problems of contrast and resolution is to instead target intrinsically faint stars.

PLANETS AROUND WHITE DWARFS

White dwarfs are intrinsically faint stars and can be up to $10,000$ times less luminous than their main sequence progenitors, significantly enhancing the contrast between any companion and the white dwarf. In addition, any companion that avoids direct contact with the red giant envelope as the main sequence progenitor evolves into a white dwarf, i.e., planets with an initial orbital radius larger than ~ 5 AU, will migrate outwards as mass is lost from the central star by a maximum factor of $M_{\rm MS}/M_{\rm WD}$ [19]. This increases the projected physical separation between the companion and the white dwarf, substantially increasing the probability of obtaining a ground based direct image of a planetary mass companion. The evolution of planetary systems during the post-main sequence phase is discussed in more detail by Duncan and Lissauer [11], Burleigh et al. [5], Debes and Sigurdsson [8] and Villaver and Livio [31].

The direct detection of a planetary mass companion in orbit around a white dwarf would allow the spectroscopic investigation of very low mass objects cooler (< 500 K) and older ($>$ few Gyr) than previously found. Such a discovery would help provide constraints on models for the evolution of planets and planetary systems during the final stages of stellar evolution. In addition, the age of any substellar and planetary mass companions discovered in such a system can be estimated using the white dwarf cooling age and the mass and the lifetime of the main sequence progenitor, providing model-free benchmark estimates of their mass and luminosity, which could be used to test evolutionary models [27]. Furthermore, as the $1.5-8\,M_\odot$ progenitor stars of white dwarfs have spectral types of early B, A and mid-F, searching for planetary mass companions in orbit around white dwarfs allows the examination of a currently inadequately explored region of parameter space, supplying new information on the frequency and mass distribution of extrasolar planets around intermediate mass main sequence stars. Finally, given that white dwarfs evolve from $1.5-8\,M_\odot$ progenitor stars, it is possible that they harbour more massive planetary companions (cf. the massive planets in wide orbits around the A-type star HR 8799), increasing the chances of directly detecting planets around white dwarfs.

An initial sample of ~ 40 targets, with total ages (main sequence progenitor lifetime plus the white dwarf cooling age) < 4 Gyr were selected from the catalogue of white dwarfs within 20 pc [18]. One hour multi-epoch observations of these white dwarfs were acquired in the J band using Gemini North and *NIRI* for equatorial and Northern hemisphere targets, and ESO-VLT and *ISAAC* for Southern hemisphere targets, while a small number of observations of equatorial targets were acquired using Gemini South and *FLAMINGOS*. These one hour J band images have an average sensitivity of $J \sim 22.5$ mag and a typical image quality of $\sim 0.6''$, without the use of adaptive optics. Due to the large number of faint objects in these deep, wide field ($120''$) images, all targets are observed again after 1–2 years to determine whether there are any common proper motion companions to the white dwarf.

The effective temperature, $T_{\rm eff}$, the log g and the mass, $M_{\rm WD}$, of the white dwarf are taken from the literature (e.g., Bergeron et al. 3, Dufour et al. 10). The cooling age of a white dwarf, $t_{\rm WD}$, can be calculated using evolutionary models. When the cooling age was unavailable in the literature, models from Fontaine et al. [14], which use $T_{\rm eff}$ and log g values to calculate the cooling age, were used to estimate this value. The initial-

final mass relation (IFMR) determined by Dobbie et al. [9], based on the measurements of a small number of white dwarfs found in young open clusters, was used to determine the mass of the main sequence progenitor, M_{MS}, from M_{WD}. This linear IFMR is given as

$$M_{\mathrm{WD}} = 0.133\,M_{\mathrm{MS}} + 0.289 \tag{1}$$

Recent observations of white dwarfs in older open clusters have placed constraints on the low mass end of the IFMR, suggesting that this equation is valid down to white dwarf masses of $0.54\,M_{\odot}$ [20]. The main sequence progenitor lifetime, t_{MS}, is estimated using the equation

$$t_{\mathrm{MS}} = 10\left(\frac{M_{\mathrm{MS}}}{M_{\odot}}\right)^{-2.5} \tag{2}$$

where t_{MS} is measured in Gyr [32]. Finally, the completeness limit for each image was estimated by determining the magnitude at which 90% and 50% of inserted artificial stars were recovered from each image. The "COND" evolutionary models for cool brown dwarfs and extrasolar planets [2], along with the magnitudes at which 90% and 50% of artificial stars were recovered, were then used to estimate the minimum mass and corresponding effective temperature of a companion that could be detected in both epoch images.

The total age of the white dwarf is equal to the sum of the main sequence progenitor lifetime and white dwarf cooling age, both of which depend upon evolutionary models. While the cooling age errors are small and well constrained [14], and the scatter in the empirical IFMR is significantly reducing as more and higher quality observations are made of white dwarfs in open clusters [6], the main sequence progenitor lifetimes rely on models that are difficult to calibrate (e.g., Catalán et al. 7). Therefore, to take these uncertainties into account, a conservative error of $\pm 25\%$ is applied to the total age of each white dwarf (note that the white dwarf cooling age is the dominant timescale for most of the targets in the DODO survey). However, at ages > 1 Gyr, the "COND" evolutionary models indicate that the absolute magnitudes of substellar objects are relatively insensitive to changes in their age, implying that even with a $\pm 25\%$ error, the resulting error on the mass of a companion is small (Table 1).

RESULTS

In Hogan et al. [16], we presented the results of 23 nearby equatorial and Northern hemisphere white dwarfs. We ruled out the presence of any common proper motion companions, with limiting masses determined from the completeness limit of each observation, to 18 white dwarfs. For the remaining five targets, the motion of the white dwarf was not sufficiently separated from the non-moving background objects in each field. Third epoch images have now been obtained for four of these five white dwarfs. These more recent observations rule out the presence of any common proper motion companions to the four white dwarfs. Since then, five Southern hemisphere white dwarfs have been fully analysed and also show no evidence of any common proper motion companions [15]. Including the non-detection of a companion around WD $0046+051$

TABLE 1. Results for 29 white dwarfs from the DODO survey

White* Dwarf	Spectral Class	t_{tot} [Gyr]	50% J [mag]	50% M [M_{Jup}]	50% T [K]	WD Orbit [AU]	MS Orbit [AU]
WD0046 + 051	DZ	3.8	22.7	7^{+0}_{-1}	290	13 - 190	3 - 48
WD0115 + 159	DQ	1.7	22.0	8^{+1}_{-1}	380	46 - 675	11 - 160
WD0141 − 675	DA	3.1	22.2	8^{+2}_{-1}	320	29 - 483	7 - 123
WD0148 + 467	DA	2.5	21.9	10^{+2}_{-1}	390	48 - 457	14 - 138
WD0208 + 396	DAZ	2.6	22.5	9^{+1}_{-1}	360	50 - 758	13 - 194
WD0341 + 182	DQ	3.3	22.9	10^{+2}_{-1}	360	57 - 801	16 - 222
WD0435 − 088	DQ	4.1	22.7	9^{+1}_{-2}	320	28 - 408	9 - 124
WD0644 + 375	DA	2.1	22.4	8^{+1}_{-1}	360	46 - 652	17 - 236
WD0738 − 172	DZ	2.4	22.0	7^{+1}_{-1}	320	27 - 379	7 - 96
WD0912 + 536	DCP	3.0	22.1	9^{+1}_{-2}	350	31 - 419	7 - 93
WD1055 − 072	DC	3.3	22.6	9^{+1}_{-1}	340	36 - 503	8 - 103
WD1121 + 216	DA	2.3	22.2	8^{+2}_{-1}	350	40 - 605	9 - 134
WD1134 + 300	DA	0.37	21.9	3^{+1}_{-0}	350	46 - 664	9 - 127
WD1236 − 495	DA	1.4	21.9	8^{+0}_{-2}	400	49 - 987	9 - 185
WD1344 + 106	DAZ	2.5	22.0	13^{+0}_{-2}	440	60 - 865	14 - 208
WD1609 + 135	DA	2.8	22.5	10^{+2}_{-1}	380	55 - 642	10 - 117
WD1626 + 368	DZ	2.2	22.8	8^{+1}_{-1}	360	48 - 535	13 - 141
WD1633 + 433	DAZ	3.0	22.3	10^{+2}_{-2}	370	45 - 533	10 - 123
WD1647 + 591	DAV	0.91	22.0	5^{+0}_{-1}	350	33 - 372	7 - 77
WD1900 + 705	DAP	1.1	22.2	5^{+1}_{-0}	330	39 - 452	8 - 89
WD1953 − 011	DAP	2.1	21.7	8^{+1}_{-1}	360	34 - 509	7 - 111
WD2007 − 219	DA	1.4	22.4	7^{+1}_{-1}	370	55 - 831	12 - 189
WD2007 − 303	DA	1.7	22.3	7^{+2}_{-1}	360	46 - 834	12 - 224
WD2047 + 372	DA	0.89	21.8	6^{+1}_{-0}	390	54 - 202	12 - 46
WD2105 − 820	DA	1.3	21.1	9^{+1}_{-1}	430	51 - 639	11 - 137
WD2140 + 207	DQ	4.4	21.6	13^{+3}_{-0}	370	38 - 542	13 - 181
WD2246 + 223	DA	1.7	22.0	9^{+1}_{-1}	400	57 - 835	11 - 157
WD2326 + 049	DAZ	1.1	21.8	6^{+1}_{-1}	370	41 - 396	9 - 89
WD2359 − 434	DA	2.9	22.3	7^{+1}_{-1}	310	24 - 433	4 - 82

* Columns: t_{tot} is the "COND" evolutionary model age used; 50% gives the 50% completeness limits in terms of apparent J magnitude, mass, M, measured in Jupiter masses, and effective temperature, T, measured in Kelvin, respectively; WD Orbit is the range of projected physical separations at which a companion of that mass could be found around the white dwarf, measured in AU; MS Orbit is the range of projected physical separations at which a companion of that mass could be found around the main sequence progenitor, measured in AU.

[4], a total of 29 white dwarfs from the DODO survey have been fully analysed (Table 1).

SUMMARY

From these results, tentative conclusions regarding the frequency of substellar and planetary mass companions to white dwarfs and their main sequence progenitors at wide separations can be made (we recognise that the DODO survey contains a relatively small number of targets). These conclusions assume that no common proper motion

TABLE 2. Recent imaging searches for wide companions

Survey*	Targets	Number of Targets	Limit [M_{Jup}]	Separation [AU]	Frequency of Companions
(1)	G K M	102	> 12	75 - 300	$1\% \pm 1\%$
		178	> 30	140 - 1200	$0.7\% \pm 0.7\%$
			5-10	75 - 300	$< 3\%$
(2)	White Dwarfs	261	> 52	100 - 5000	$< 0.5\%$
		86	> 21	50 - 1100	$< 0.5\%$
(3)	M7-L8	132	> 52	40 - 1000	$< 2.3\%$
(4)	F G K M	85	13-40	25 - 250	$< 5.6\%$
(5)	A F G K M	60	> 4	20 - 100	$< 20\%$
(6)	White Dwarfs	29	>10	60 - 200	$< 8\%$

* (1) McCarthy and Zuckerman [24]; (2) Farihi et al. [13]; (3) Allen et al. [1]; (4) Lafrenière et al. [22]; (5) Nielsen et al. [26]; (6) Hogan et al. [16]

companions are confirmed around the remaining white dwarf requiring a third epoch image. Firstly, using the 90% completeness limits, the DODO survey can detect companions with effective temperatures > 540 K around *all* targets. Therefore, we suggest that $< 4\%$ of white dwarfs have substellar companions with effective temperatures > 540 K between projected physical separations of $60 - 200$ AU, although for many fields this applies to smaller (~ 13 AU for WD $0046+051$; Burleigh et al. 4) and larger (~ 1000 AU) projected physical separations. This corresponds to projected physical separations around their main sequence progenitors ($1.5 - 8\,M_{\odot}$, i.e., spectral types F5–B5) of $20 - 45$ AU, although again for many fields these limits apply to smaller (~ 3 AU for WD $0046+051$; Burleigh et al. 4) and larger (~ 230 AU) projected physical separations. For the same range of projected physical separations around both white dwarfs and main sequence progenitors and using the 50% completeness limits, we suggest that $< 7\%$ of white dwarfs and their main sequence progenitors have companions with masses above the deuterium burning limit ($\sim 13\,M_{\rm Jup}$), while $< 8\%$ have companions with masses $> 10\,M_{\rm Jup}$.

The results from the DODO survey can be compared to the results from other imaging surveys for wide substellar and planetary mass companions to white dwarfs and main sequence stars (Table 2). In particular, our results are consistent with those of McCarthy and Zuckerman [24] and Lafrenière et al. [22]. The DODO survey results can also be compared to complimentary recent MIR searches for *unresolved* substellar and planetary mass companions to white dwarfs (e.g., Mullally et al. 25). A recent MIR photometric survey of 27 white dwarfs using the Spitzer Space Telescope and IRAC, which was performed by Farihi et al. [12], was sensitive to the entire known T dwarf sequence. Their observations place similar limits ($< 4\%$) on the frequency of such companions to white dwarfs, but at smaller separations (with some overlap) compared to the DODO survey.

FUTURE WORK

Since the DODO survey contains a relatively small number of targets, increasing the number of white dwarfs observed will increase the likelihood of directly detecting a planet around a white dwarf. Additional white dwarfs have recently been discovered in the local neighbourhood (e.g., Subasavage et al. 28, Holberg et al. 17, Subasavage et al. 29, Subasavage et al. 30), which has provided the opportunity to extend the DODO survey. First epoch images of 10 new white dwarfs within $\sim$ 40 pc have already been obtained with Gemini North and *NIRI*, and a proposal to obtain the second epoch images for these white dwarfs will be submitted next year.

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REFERENCES

1. P. R. Allen, D. W. Koerner, M. W. McElwain, et al., *AJ* **133**, 971–978 (2007).
2. I. Baraffe, G. Chabrier, T. S. Barman, et al., *A&A* **402**, 701–712 (2003).
3. P. Bergeron, S. K. Leggett, and M. T. Ruiz, *ApJS* **133**, 413–449 (2001).
4. M. R. Burleigh, F. J. Clarke, E. Hogan, et al., *MNRAS* pp. L3–9 (2008).
5. M. R. Burleigh, F. J. Clarke, and S. T. Hodgkin, *MNRAS* **331**, L41–L45 (2002).
6. S. L. Casewell, P. D. Dobbie, R. Napiwotzki, et al., *MNRAS* **395**, 1795–1804 (2009).
7. S. Catalán, J. Isern, E. García-Berro, et al., *A&A* **477**, 213–221 (2008).
8. J. H. Debes, and S. Sigurdsson, *ApJ* **572**, 556–565 (2002).
9. P. D. Dobbie, R. Napiwotzki, M. R. Burleigh, et al., *MNRAS* **369**, 383–389 (2006).
10. P. Dufour, P. Bergeron, and G. Fontaine, *ApJ* **627**, 404–417 (2005).
11. M. J. Duncan, and J. J. Lissauer, *Icarus* **134**, 303–310 (1998).
12. J. Farihi, E. E. Becklin, and B. Zuckerman, *ApJ* **681**, 1470–1483 (2008).
13. J. Farihi, E. E. Becklin, and B. Zuckerman, *ApJS* **161**, 394–428 (2005).
14. G. Fontaine, P. Brassard, and P. Bergeron, *PASP* **113**, 409–435 (2001).
15. E. Hogan, F. J. Clarke, and M. R. Burleigh, *MNRAS* **in prep.** (2010).
16. E. Hogan, M. R. Burleigh, and F. J. Clarke, *MNRAS* **369**, 2074–2086 (2009).
17. J. B. Holberg, E. M. Sion, T. Oswalt, et al., *AJ* **135**, 1225–1238 (2008).
18. J. B. Holberg, T. D. Oswalt, and E. M. Sion, *ApJ* **571**, 512–518 (2002).
19. J. H. Jeans, *MNRAS* **85**, 2–11 (1924).
20. J. S. Kalirai, B. M. S. Hansen, D. D. Kelson, et al., *ApJ* **676**, 594–609 (2008).
21. D. Lafrenière, R. Jayawardhana, and M. H. van Kerkwijk, *ApJ* **689**, L153–L156 (2008).
22. D. Lafrenière, R. Doyon, C. Marois, et al., *ApJ* **670**, 1367–1390 (2007).
23. C. Marois, B. Macintosh, T. Barman, et al., *Science* **322**, 1348–1352 (2008).
24. C. McCarthy, and B. Zuckerman, *AJ* **127**, 2871–2884 (2004).
25. F. Mullally, M. Kilic, W. T. Reach, et al., *ApJS* **171**, 206–218 (2007).
26. E. L. Nielsen, L. M. Close, B. A. Biller, et al., *ApJ* **674**, 466–481 (2008).

27. D. J. Pinfield, H. R. A. Jones, P. W. Lucas, et al., *MNRAS* **368**, 1281–1295 (2006).
28. J. P. Subasavage, T. J. Henry, P. Bergeron, et al., *AJ* **134**, 252–261 (2007).
29. J. P. Subasavage, T. J. Henry, P. Bergeron, et al., *AJ* **136**, 899–908 (2008).
30. J. P. Subasavage, W. Jao, T. J. Henry, et al., *AJ* **137**, 4547–4560 (2009).
31. E. Villaver, and M. Livio, *ApJ* **661**, 1192–1201 (2007).
32. M. A. Wood, *ApJ* **386**, 539–561 (1992).